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Mechanical Characterisation of Structural Laminated Bamboo

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Abstract

Low carbon construction materials are needed to reduce CO_2 emissions in the built environment. Laminated bamboo is an example of such a material, however to be used in structural applications, fundamental mechanical properties are needed to establish the design values used in architecture and engineering practice. Recent studies on laminated bamboo have focused on the use of timber standards for small clear specimens, with little work published on structural scale testing. The presented work is the first study to utilise structural scale test methods for timber in a multi-laboratory test programme to investigate all mechanical properties of an outdoor laminated bamboo product. The study provides a comparison of the full scale structural performance to conventional timber and a pathway for use in engineering design and practice. The study shows laminated bamboo is comparable to conventional timber and timber-based products in structural properties and forms the foundation to use laminated bamboo in design and construction.

Keywords

Bamboo; Buildings, structures & design; Strength and testing of materials; Timber structures.

List of notation

a	is the distance between the load introduction point and nearest support,
b	is the specimen width
$E_{c,0}$	is the local compressive modulus parallel to grain
$E_{c,0,mean}$	is the mean local compressive modulus parallel to grain
$E_{c,90}$	is the local compressive modulus perpendicular to grain

$E_{c,90,mean}$	is the mean local compressive modulus perpendicular to grain
$E_{t,0}$	is the local tensile modulus parallel to grain
$E_{t,0,mean}$	is the mean local tensile modulus parallel to grain
E_m	is the local bending modulus
$E_{m,mean}$	is the mean local bending modulus
$E_{t,90}$	is the local tensile modulus perpendicular to grain
$E_{t,90,mean}$	is the mean local tensile modulus perpendicular to grain
$f_{c,0,mean}$	is the mean compressive stress parallel to grain
$f_{c,90,mean}$	is the mean compressive stress perpendicular to grain
$f_{m,mean}$	is the mean bending modulus of rupture
$f_{t,0,mean}$	is the mean tensile stress parallel to grain
$f_{t,90,mean}$	is the mean tensile stress perpendicular to grain
$f_{v,0,mean}$	is the mean shear stress parallel to grain
h	is the specimen height
h_0	is the measuring length for the local E-modulus
I	is the second moment of inertia of the specimen cross-section
k	is the index for the characteristic strength value
l	is the specimen length
l_1	is the measuring length for the E-modulus
COV	is the coefficient of variation
EW	is the edgewise orientation
FW	is the flatwise orientation
ρ_{mean}	is the mean density
u_{mean}	is the mean moisture content
α	is the Weibull scale parameter
β	is the Weibull shape parameter
µ	is the mean value
μ_0	is the median value

1. Introduction

Laminated bamboo is increasingly investigated globally for structural applications as a sustainable material for construction. The material has been shown to be a low-carbon alternative (van der Lugt et al., 2006; van der Lugt, 2008; van der Lugt et al., 2009; Vogtlander et al., 2010; van der Lugt and Vogtlander, 2015), however the use of the material is limited due to the lack of fundamental mechanical properties for design. Further, to be included in design standards, characteristic values based on experimental test methods are necessary, which requires extensive testing. The structural applications of laminated bamboo have been demonstrated in full scale construction and vary from short span bridges to two-storey housing (Xiao, 2016). The studies show that the material can be effectively used as a construction material (Huang et al., 2013; Xiao et al., 2010; Xiao, 2016). Although global research has explored the use of laminated bamboo in structural applications, the studies typically focus on small clear specimens to establish mechanical properties (i.e. Correal et al., 2010; Sharma et al., 2015; Yang et al., 2014); comprehensive structural scale testing has yet to be fully explored.

In this study, the mechanical properties of an outdoor laminated bamboo product were investigated utilising structural scale test methods for timber, which provides a comparison of the structural behaviour of the two materials, and provides a pathway for use in engineering design and practice. To explore the variability in testing, testing was conducted between two laboratories, TU Graz, with experience in wood testing and Cambridge University, with experience in bamboo testing. Tests were divided equally when possible, or if not, conducted at a single laboratory based on the facilities available.

2. Experimental Methodology

2.1 Material

The study used a commercially produced outdoor laminated bamboo product, Moso Bamboo N-Finity (manufacturer: Moso International BV). The specimens were manufactured in China and were comprised of caramelised bamboo strips laminated with a phenol formaldehyde (PF) resin. To allow for longer members to be manufactured, a hook joint was incorporated into the material; however, it was not an engineered connection (Figure 1a). Samples were manufactured and cut to specified dimensions (Table 1) and shipped to the respective laboratories. To maintain clarity and consistency, the study uses industry terminology to describe the orientation of an individual strip of bamboo within a laminated board. A single strip is obtained from the culm wall as shown in Figure 1b. After processing, there are two commercial orientations of the individual laminate in the final board product: edgewise (Figure 1c) and flatwise (Figure 1d), which differ in the axis of the radial direction of the original culm wall. When laminated into beams, the edgewise (EW) and flatwise (FW) orientations are markedly different when viewed in cross section (Figure 1e and 1f). Where appropriate, the mechanical properties of the two orientations were investigated and the obtained strength or modulus will reference the orientation (EW or FW). The tests were conducted parallel or perpendicular to the fibre direction as indicated in the subscript. For example for compressive stress, (f_c) perpendicular to grain ($_{90}$) in the edgewise orientation ($_{EW}$) the notation is "$f_{c,90,EW}$".

2.2 Experimental Testing

The scope of testing included bending, tension and compression parallel and perpendicular to grain, as well as shear parallel to grain. The tests were conducted in accordance with EN 408: *Timber structures – Structural timber and glued laminated timber – Determination of some physical and mechanical properties* (CEN, 2012). The standard was applied to laminated bamboo using the structural timber guidelines. The specimens were stored in humidity and temperature-controlled environments prior to testing, maintained at 20°C (± 2°C) and 65 % (± 5 %) relative humidity in both laboratories. In larger specimens, the variation in thickness was documented at points along the length of the material and reported as the average. Moisture content was determined by the oven-dry method following ON ISO 13061 (ISO, 2014). Density was measured based on the full cross section of the specimen according to EN 384 (CEN, 2010) and on small specimens according to ON ISO 13061 (ISO, 2014). Table 1 summarises the specimen dimensions and quantities tested at each laboratory. The brief summary below highlights each test method. Preliminary tests were conducted to validate and determine testing parameters. In accordance with EN 408 (CEN, 2012), all tests were conducted in displacement control to achieve failure load F_{max} within 300 ± 120s.

2.2.1 Bending

Four-point bending tests were carried out at both laboratories. The test method allowed some variability in testing speed, with the average loading rate approximately 10 mm/min. The local E-modulus was determined from the displacement taken on both sides of the specimen at midspan and midheight of the specimen, as shown in Figure 2a. As per EN 408 (CEN, 2012) the local E-modulus was calculated with Equation 1:

$$E_m = \frac{a l_1^2 (F_2 - F_1)}{16 I (w_2 - w_1)} \quad 1.$$

in which a is the distance between the load introduction point and nearest support, l_1 is the measuring length for the local E-modulus, I is the second moment of inertia of the specimen cross-section, F_2-F_1 is the increase of the load in the range where the regression has a correlation coefficient of 0.99 or better and w_2-w_1 is the corresponding rise in displacement.

2.2.2 Tension perpendicular to grain

Tension perpendicular to grain testing was carried out in both laboratories. The test setup and specimen details are shown in Figure 2b. The specimens were bonded to Sitka Spruce ends using a polyurethane adhesive (Purbond HB S309) and clamped for a minimum of 24 hours before testing. The specimens were capped with a steel plate using wood screws and connected to the frame using a threaded rod fixed to a ball joint to cancel any moment (Figure 2b). The shape of the timber differed between the two laboratories due to the type of attachment to the test frames, however both were in accordance EN 408 (CEN, 2012). The test method allowed some variability in testing speed, with the average loading rate approximately 0.4-0.6 mm/min. Displacement was measured on both sides of the specimen with high accuracy extensometers over the specified gage length to obtain the local E-modulus. As per EN 408, the local E-modulus was calculated with Equation 2:

$$E_{t,90} = \frac{(F_{40} - F_{10}) h_0}{(w_{40} - w_{10}) b l} \quad 2.$$

in which F_{40}-F_{10} is the increase of the load between $0.1F_{max,est}$ and $0.4\ F_{max,est}$ and w_{40}-w_{10} is the corresponding rise in displacement, h_0 is the measuring length for the local E-modulus, b is the width of the specimen, and l is the length of the specimen.

2.2.3 Compression perpendicular to grain

Compression perpendicular to grain testing was carried out at both laboratories. The test method allowed some variability in testing speed, with the average loading rate approximately 0.4-0.6 mm/min. To obtain the local E-modulus, displacement was measured with high accuracy extensometers on both sides of the specimen over the specified gage length (Figure 2c). As per EN 408, the local E-modulus was calculated with Equation 3:

$$E_{c,90}=\frac{(F_{40}-F_{10})h_0}{(w_{40}-w_{10})bl}$$

3.

in which F_{40}-F_{10} is the increase of the load between 0.1$F_{max,est}$ and 0.4 $F_{max,est}$ and w_{40}-w_{10} is the corresponding rise in displacement, h_0 is the measuring length for the local E-modulus, *b* is the width of the specimen, and *l* is the length of the specimen.

2.2.4 Tension parallel to grain

Tension parallel to grain tests were carried out on both a single ply board (Figure 3a) and a laminated section (Figure 3b). Single ply laminated bamboo was tested at TU Graz utilising a tension testing machine (GEZU 850) in load control (Figure 3a). The end cross sections of the test specimens were gripped by clamping plates. The local E-modulus was measured with two displacement transducers on the side faces over the specified gage length. As per EN 408, the E-modulus was calculated with Equation 4:

$$E_{t,0}=\frac{l_1(F_2-F_1)}{A(w_2-w_1)}$$

4.

in which l_1 is the measuring length for the E-modulus, *A* is the cross-sectional area, F_2-F_1 is the increase of the load in the range where the regression has a correlation coefficient of 0.99 or better and w_2-w_1 is the corresponding rise in displacement.

The laminated section was tested at Cambridge University in an Amsler test frame with mechanical wedge grips that increase the gripping force with increasing load. Preliminary tests indicated that the full cross section resulted in a grip-induced failure. Modification of the rectangular section into a dogbone specimen, as shown in Figure 3b, allowed for failure to occur in the specimen. The test method allowed some variability in testing speed, with the average loading rate approximately 4.5 mm/min. Displacement was measured on the wide face of the specimen with high accuracy extensometers over the specified gage length to obtain the local E-modulus, which was calculated using Equation 4 as described above.

2.2.5 Compression parallel to grain

Compression parallel to grain testing was carried at Cambridge University. The test method allowed some variability in testing speed, with the average loading rate approximately 0.6-0.8 mm/min. The local E-modulus was obtained through displacement measurements on both sides of the specimen. Specially designed compressometers were used on either side of the specimen to measure the displacement over the specified gage length and displacement was measured using high accuracy laser extensometers (Figure 3c). As per EN 408, the E-modulus was calculated with Equation 5:

$$E_{c,0}=\frac{l_1(F_2-F_1)}{A(w_2-w_1)}$$

5.

in which l_1 is the measuring length for the E-modulus, A is the cross-sectional area, F_2-F_1 is the increase of the load in the range where the regression has a correlation coefficient of 0.99 or better and w_2-w_1 is the corresponding rise in displacement.

2.2.6 Shear

Shear parallel to grain tests were carried out at Cambridge University. The test method allowed some variability in testing speed, with the average loading rate approximately 0.7-0.9 mm/min. The test setup and specimen details are shown in Figure 3d. The specimens were bonded to 10mm thick sandblasted steel plates (Figure 3d). A high shear strength two-part epoxy (Araldite 2015) consisting of a resin and a hardener that cured at room temperature was used bond the specimens to the plate. The specimens manually clamped and left to cure for 24 hours before testing. After each test, the specimens were documented and the plates were cleaned and reused, roughening the steel plate surface for each test.

3. Results

The following sections present the results of the testing programme, which are also summarised in Table 2. Comparison of the results with other published experimental studies using EN 408 test methods are presented in Table 3. The table shows the characteristic values, when provided, from experimental studies on Norway spruce (Steiger et al., 2009; Jenkel et al., 2015), glue laminated spruce (De Lorenzis et al., 2005) and thermally modified beech wood (Widmann et al., 2012). The experimental results are shown in Figure 4 and 5. Characteristic, or nominal, values were determined as the 5th percentile as per EN 384 (CEN, 2010) and are shown in the figures and summarised in Table 2.

3.1 Bending

In both edgewise and flatwise orientations, failure at the longitudinal joint (see Figure 1a) was observed on the tension face at midspan. The bending strength and local E-modulus results from the respective test series are comparable. The results are shown in Figure 4a and b. Comparison of the laminate orientation indicates a slight increase in the bending strength (14 %) and local E-modulus (6-13 %) in the edgewise orientation (Figure 4a and b).

There is some correlation between the specimen density and bending local E-modulus, a relationship that is often observed in timber studies. In the laminated bamboo, the correlation is strongest between density and the bending modulus. The results from TU Graz in both the edgewise (R^2=0.51) and flatwise (R^2=0.56) orientations suggests a similar relationship that is common in timber. However, the results from the two labs differ greatly, with results from Cambridge University showing no correlation (edgewise R^2=0.01 and flatwise R^2=0.03), therefore, the observation is not definitive. Both laboratory results indicated the correlation between the local bending modulus and modulus of rupture is low in the edgewise orientation (R^2=0.31-0.35) and non-existent in the flatwise orientation (R^2=0.01-0.10). In comparison to timber, the correlation is typically strong (i.e., R^2=0.74) which Olsson et al. (2012) attributes to the relationship between strength and stiffness at the location of failure. The low correlation in the laminated bamboo suggests that ultimate failure may not be governed by the local bending stiffness at midspan.

3.2 Tension perpendicular to grain

In tension perpendicular to grain, the results varied between the laboratories (Figure 4c and d). As shown in the figure, the Cambridge University results showed a higher coefficient of variation (COV) in tensile strength (COV = 0.32) and local E-modulus (COV = 0.24). The flatwise orientation has a slightly better strength and modulus (~10%) in comparison to the edgewise orientation.

3.3 Compression perpendicular to grain

In compression perpendicular to grain, the typical failure was splitting of the individual laminates. The results from Cambridge University had a higher strength and coefficient of variation compared to the TU Graz results (Figure 4e). The opposite trend was observed in the local E-modulus, with the Cambridge University measurements nearly 7% lower than the mean determined in TU Graz (Figure 4f). The two laboratories utilised different measurement sensors, but with the same accuracy, so it is unclear whether the variation is material- or test-based. There was a slight increase in strength in the edgewise orientation and a small decrease in the local E-modulus.

3.4 Tension parallel to grain

The tension parallel to grain tests utilised two types of specimens (full-scale and small sample) and thus were not combined into a single data set. A 30% increase in mean tensile strength and an 8% increase in mean local modulus was observed in the dogbone specimen compared to the single ply (Figure 5a and b). The wider distribution of the joints in the laminated section may be the source of the increase in strength, however further investigation is need to determine in-service performance. The failure mode of the material was similar between the single ply and laminated section, with the failure dominated by a brittle failure in the longitudinal direction.

3.5 Compression parallel to grain

In compression parallel to grain, the tests were conducted at Cambridge University and the results were repeatable for both the compressive stress (COV = 0.07) and E-modulus (COV = 0.08), as shown in Figure 5c and d. The ultimate failure of the material was in buckling, representing the strength of the sample dimension and aspect ratio, rather than the ultimate strength. The buckling behaviour differs from the expected shear failure in timber, yet it is consistent with other compression studies on laminated bamboo (Huang et al., 2013; Li et al., 2013). Research has been conducted on the influence of the aspect ratio on the compressive strength (i.e. Li et al., 2015), however additional work is needed to determine the appropriate test parameters to obtain the ultimate strength of the material.

3.6 Shear parallel to grain

The two orientations had comparable shear strengths, however the variability between the orientations differed significantly (Figure 5e). The edgewise orientation had approximately twice the coefficient of variation (COV=0.18) than the flatwise orientation (COV=0.08). In accordance with EN 408 (CEN, 2012), specimens with greater than 20% failure in the plate-specimen interface were excluded from the analysis, which was approximately half of the samples.

For comparison, all of the results are shown in Figure 5e. The strength difference between the two orientations was negligible. The results suggest a larger sample size is needed to full characterise the shear strength of the material. The correlation between the density and shear stress parallel to grain is moderate with the edgewise orientation indicating a stronger correlation (R^2=0.42) than the edgewise (R^2=0.18). The sample size of the tests was small due to the exclusion of results due to failure in the interface, therefore further testing is needed to evaluate the relationship, if any, between the properties.

3.6 Density

As noted in table 2, the mean density for all samples was 666 kg/m^3 (COV = 0.05). Figure 5f shows the variation in density for all specimens, with each type of test categorised by orientation: edgewise, flatwise and no orientation for parallel to grain compression and tension. The bending specimens have significant variation in density within and between laboratories, for both orientations, which may contribute to the differences in strength that were observed. Figure 5f also displays the comparable density between the edgewise compression and tension perpendicular to grain samples, suggesting the specimens were manufactured from the same batch. In contrast, the flatwise orientation specimens have greater variation within and between laboratories in all tests. The density did not correlate strongly with the strength properties, with the exception of the local bending modulus and shear strength. Further investigation of the fibre volume fraction, density and strength would elucidate relationships, if any, between the properties.

4. Statistical Analysis

In addition to the determination of the mechanical properties, the present study provided an opportunity to explore uncertainty of experimental testing through comparison of the individual laboratory results. Due to the large variation between the laboratories, the test results (bending, and perpendicular to grain tension and compression) were analysed using a two sample t-test using SPSS (IBM Corp., 2013; Quirk, 2015). The hypothesis was that the mean population means are equal (H_0: $\mu_1 = \mu_2$) and the alternate that they are unequal (H_A: $\mu_1 \neq \mu_2$). The single source data sets (compression, tension and shear parallel to grain) were analysed to test the median value (μ_0) as a hypothetical mean (H_0: $\mu_0 = \mu$) using a t-test, with $\alpha=0.05$. The results of the analysis are presented and discussed below.

4.1 Bending

The analysis accepted the null hypothesis and indicated the flatwise orientation bending stress was not significant (p-value = 0.09). The null hypothesis was rejected for the flatwise orientation local E-modulus which was borderline significant ($0.01 \leq$ p-value ≤ 0.05), and highly significant (p-value ≤ 0.005) for the edgewise orientation in both the bending stress and local E-modulus. The analysis indicates that the variation between the two data sets is significant and they cannot be pooled.

4.2 Tension Perpendicular to Grain

The statistical analysis was not significant (p-value > 0.05) for all results with the exception of the flatwise tensile local E-modulus which was borderline significant (0.01 ≤ p-value ≤ 0.05). The results indicate the data that can be pooled into a single source. Comparison of the two orientations shows less variation in the flatwise tensile stress perpendicular to grain (p-value =0.67) than the edgewise orientation (p-value = 0.15).

4.3 Compression Perpendicular to Grain

For the perpendicular to grain compression stress and the local E-modulus the analysis was not significant (p-value > 0.05) in the edgewise orientation. The flatwise orientation was highly significant for the perpendicular to grain compressive stress and local E-modulus (p-value ≤ 0.005). The results indicate that the edgewise orientation results can be pooled and the flatwise cannot.

4.4 Compression Parallel to Grain

For the compression parallel to grain, the median stress (μ_0=39 MPa) was selected as the test statistic to compare the hypothesis (μ_0=μ). The t-test analysis indicated that it is indicative of the population mean (p-value > 0.05). For the compressive local E-modulus parallel to grain, the median was hypothesised as (μ_0=8250 MPa) and the t-test indicated that it is representative of the population mean (p-value > 0.05).

4.5 Tension Parallel to Grain

Two different test methods were used to determine the tension parallel grain strength and local E-modulus, thus the data sets were not combined. In the single-ply tests, the median stress (μ_0=39 MPa) and median modulus (μ_0=7997 MPa) were selected as the test statistics to compare the hypothesis (μ_0=μ). The analysis indicated that both values are representative of the population mean (p-value > 0.05). For the laminated section, the median stress (μ_0=49 MPa) and median modulus (μ_0=8532 MPa) were selected as the test statistics to compare the hypothesis (μ_0=μ). The analysis indicated that both values are representative of the population mean (p-value > 0.05).

4.6 Shear Parallel to Grain

For the shear parallel to grain, two orientations were tested. The analysis was applied to the specimens that passed the <20% failure in the interface as per the standard. In the edgewise orientation, the median stress (μ_0=7.1 MPa) was selected as the test statistic to compare the hypothesis ($\mu_0=\mu$) and was indicative of the population mean (p-value > 0.05). For the flatwise orientation, the median stress (μ_0=7.6 MPa) was determined to be representative of the population mean (p-value > 0.05).

4.7 Statistical Comparison of Parallel Testing

The results indicate that there is significant variation between the two laboratories, which can be attributed to material variation, as well as variation in machinery and test methods. Although the material was obtained from the same batch, the rejection of the null hypothesis (H_0: $\mu_1= \mu_2$) indicates that the experimental results are not from the same population and therefore cannot be pooled. The null hypothesis is not probable even if the samples were conducted by the same operator, however testing parameters, such as variable loading rate and measurement devices, may have had influence on the results. The study suggests that existing timber test methods provide a foundation from which to develop engineered bamboo standards, but additional investigation is required to determine the appropriate test parameters. Furthermore, while the sample size was determined in accordance with EN 408 (CEN, 2012), the variation suggests a larger number of samples are required to obtain an accurate estimate of the material strength. To explore the reliability of the mechanical properties in comparison to the characteristic values, the sample distributions were further investigated.

5. Weibull Two-Parameter Cumulative Distribution Functions

Bamboo is an anisotropic material with significant variation in both raw and processed material. Reliability-based failure methods have been explored in composite materials to predict and model performance (Barbero et al., 2000), as well as graded timber (Faber et al., 2004). A reliability-based approach for engineered bamboo would provide a way in which to account for uncertainty and variation in materials, as well as testing methods. To investigate the use of reliability-based failure prediction, a cumulative distribution function of a two-parameter Weibull distribution is shown in Equation 6 (Weibull, 1951):

$$F(q)=1-\exp\left[-\left(\frac{q}{\alpha}\right)^{\beta}\right]$$

6.

where F is the probability of failure, q the property under investigation, β is a shape parameter, and α is the scale parameter for the distribution. The results from the laboratory testing were used to determine q using a median rank estimator and the two parameters (α and β) were determined using linear regression. Reliability is given in Equation 7 as:

$$R(q)=\exp\left[-\left(\frac{q}{\alpha}\right)^{\beta}\right]$$

7.

The reliability plots for the mechanical properties are shown in Figures 6 and 7. The two laboratories are differentiated by markers, with TU Graz indicated with a triangle and Cambridge University represented by a circle. The dashed lines indicate the edgewise orientation and the flatwise orientations are represented with solid lines. In the tension and compression parallel to grain tests there is no orientation and a solid line is used. The characteristic stress is shown with the grey shaded area. The scale (α) and shape (β) parameters for each data set are indicated in the figures.

As expected, the characteristic values represent a conservative estimate of predicted strength. The reliability curves provide a preliminary investigation of where there are areas of acceptable stress and where the reliability drastically changes. In particular, the shear strength parallel to grain illustrates a drastic change in the failure stress (Figure 7e). The accuracy of this estimate would be improved by additional testing to increase the sample size.

Specimen density is shown in Figure 7f, with the characteristic density (641 kg/m^3) highlighted by the grey line. In comparison to the other properties, the characteristic density has slightly lower reliability (~0.8). This reflects the inherent material and manufacturing variability, which requires additional investigation. Furthermore, the reliability curve provides a basis to explore grading of engineered bamboo, building upon reliability-based grading methods for timber (Faber et al., 2004; Kohler et al., 2007; Steiger and Arnold, 2009). As discussed in the previous section, the correlation of density and strength was moderate for the bending modulus and shear strength. The other properties do not have a clear relationship that can be developed for grading of engineered bamboo.

Reliability-based failure prediction is a potential method to form the foundation for characterisation of mechanical properties and can be expanded to building component performance. In comparison to traditional empirically-based design methods, which rely on significant experimental testing, reliability methods, combined with some experimental testing, would allow for determination of lower bound confidence intervals. Further, multiple random material property values can be generated for use in numerical modelling. This approach would allow for greater exploration of the material, particularly in innovative structures and structural components and systems.

6. Timber test standards for laminated bamboo

Through the application of timber standards, the mechanical properties of laminated bamboo can be obtained. The study allowed for the direct comparison to timber and timber-based products using structural scale testing standards. Standards, such as EN 408 (CEN, 2012), have been developed specifically for the behaviour of timber and further work is needed to evaluate testing parameters to determine influences, if any, on the structural properties obtained from testing. Factors such as loading rate, gage length for modulus of elasticity, as well as specimen dimensions, need to be established with consideration of the inherent properties of laminated bamboo. The study demonstrated that timber standards and design codes are a pathway to characterisation of the material and form the foundation for moving the field forward towards adoption and in design and engineering practice.

7. Summary

In conclusion, the study presented is the first to characterise structural properties of engineered bamboo based on full-scale structural timber testing standards. The study was conducted through parallel testing at TU Graz and the University of Cambridge. Multi-laboratory testing allows for assessment of uncertainty, as well as the variation of testing parameters. The results show that laminated bamboo has properties that are comparable to timber and glue-laminated timber products. The study is considered a lower-bound estimate of strength, as the location of failure was often at a non-engineered joint used to manufacture longer lengths. Additional research is needed on the development of a ‘finger joint’ to create longer lengths and spans in laminated bamboo. The flexibility of material is a unique and differs greatly from timber, suggesting that there is greater potential for the material in innovative structural design.

Comparison of the results from the two laboratories revealed that while the tests produced similar results, the variation within and between the laboratories differed significantly. The study indicates that to determine the source of variation in testing, as well as the validity of the timber testing standard in regard to engineered bamboo. The use of reliability analysis to obtain characteristic values for design was presented to explore the potential for future standardisation of the materials. Overall, the study validated the need for globalised standard test methods for characterisation and the advantage of multi-laboratory testing in assessing uncertainty. The presented work showed that a combined approach to characterisation and standardisation is needed to move engineered bamboo toward an accepted material for design and engineering practice.

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Table Captions.

Table 1. Summary of specimen dimensions and sample sizes.

Table 2. Summary of experimental test results and characteristic values for laminated bamboo. TU Graz values are shown in white, Cambridge University values are shown in grey. The coefficient of variation (COV) is shown in parentheses.

Table 3. Comparison of characteristic strength, stiffness properties (mean values) and density (mean values) for laminated bamboo, strength classes for structural timber and glulam and experimental testing parallel to grain in accordance with EN 408.

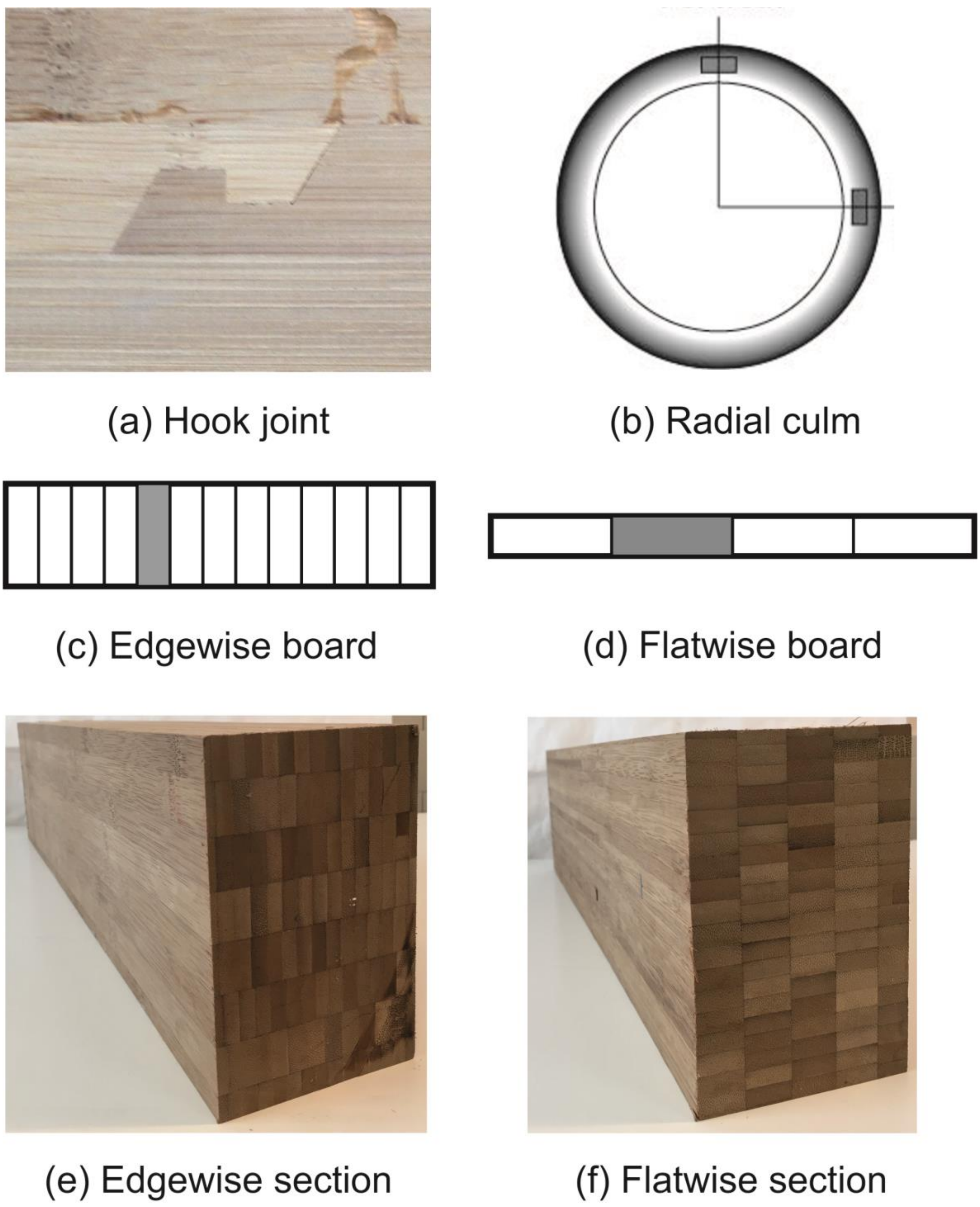


Figure 1. Industry terminology for laminate orientation within a single board.

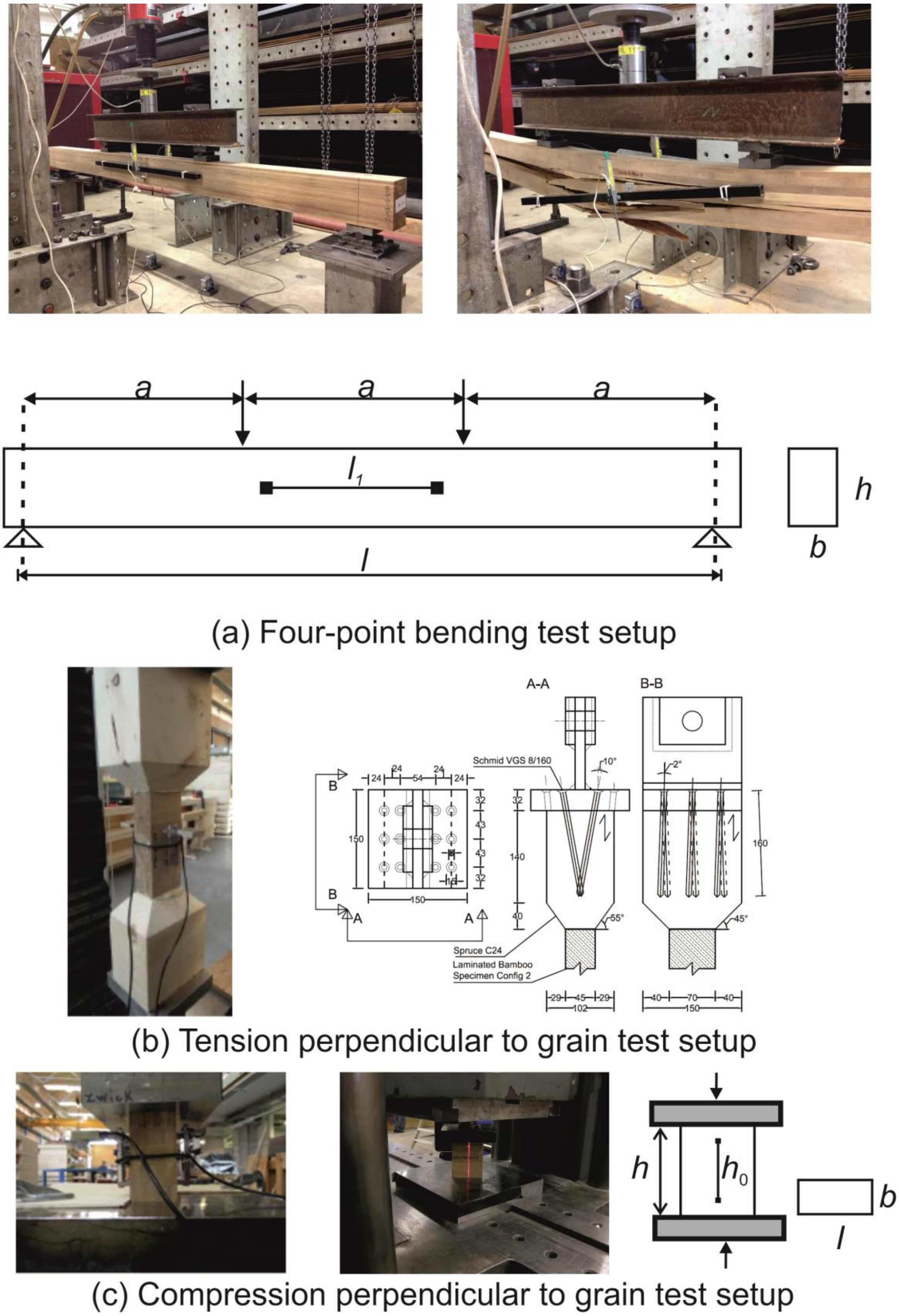
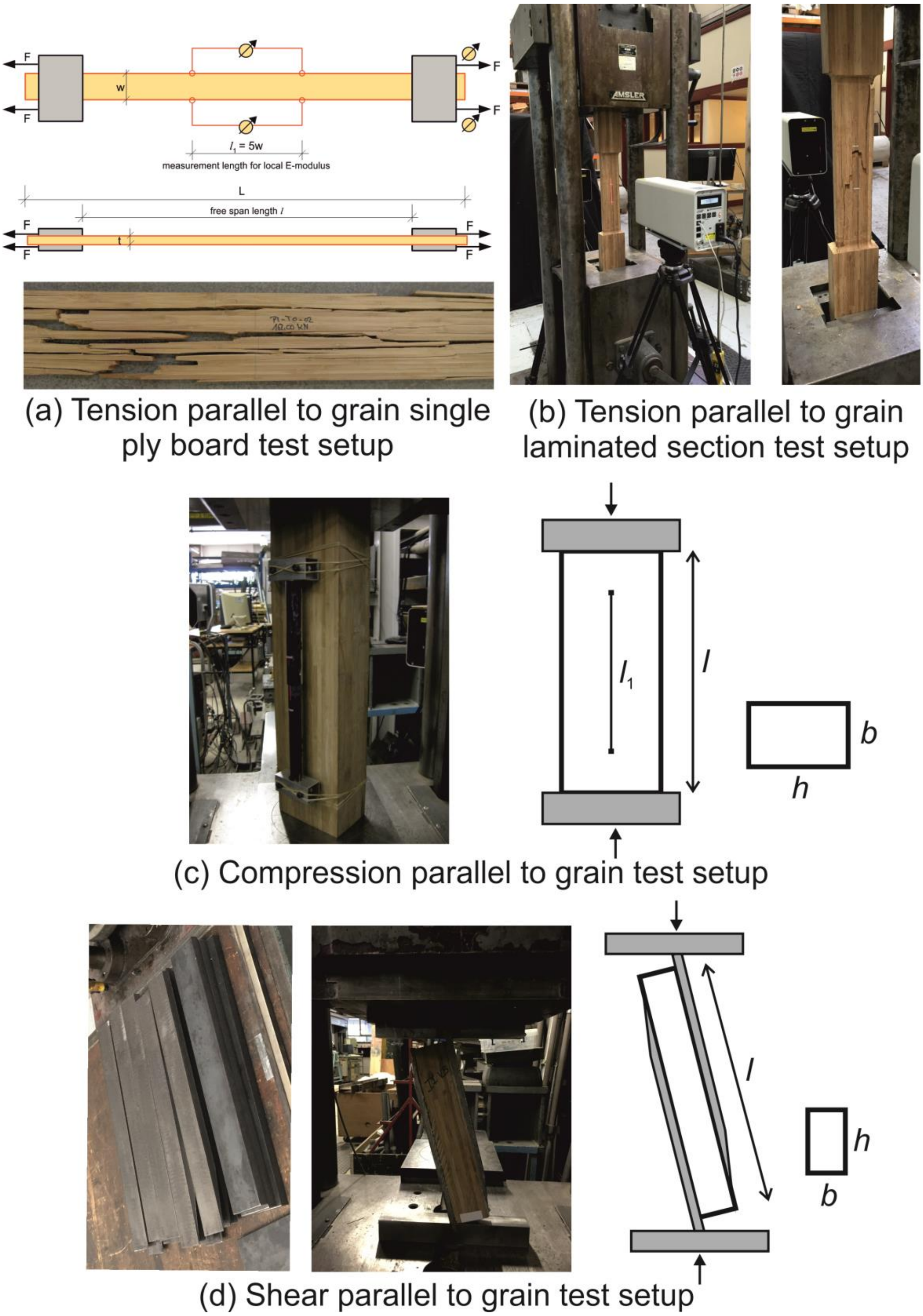


Figure 2. Experimental test methods: (a) bending, (b) tension and (c) compression perpendicular to grain.



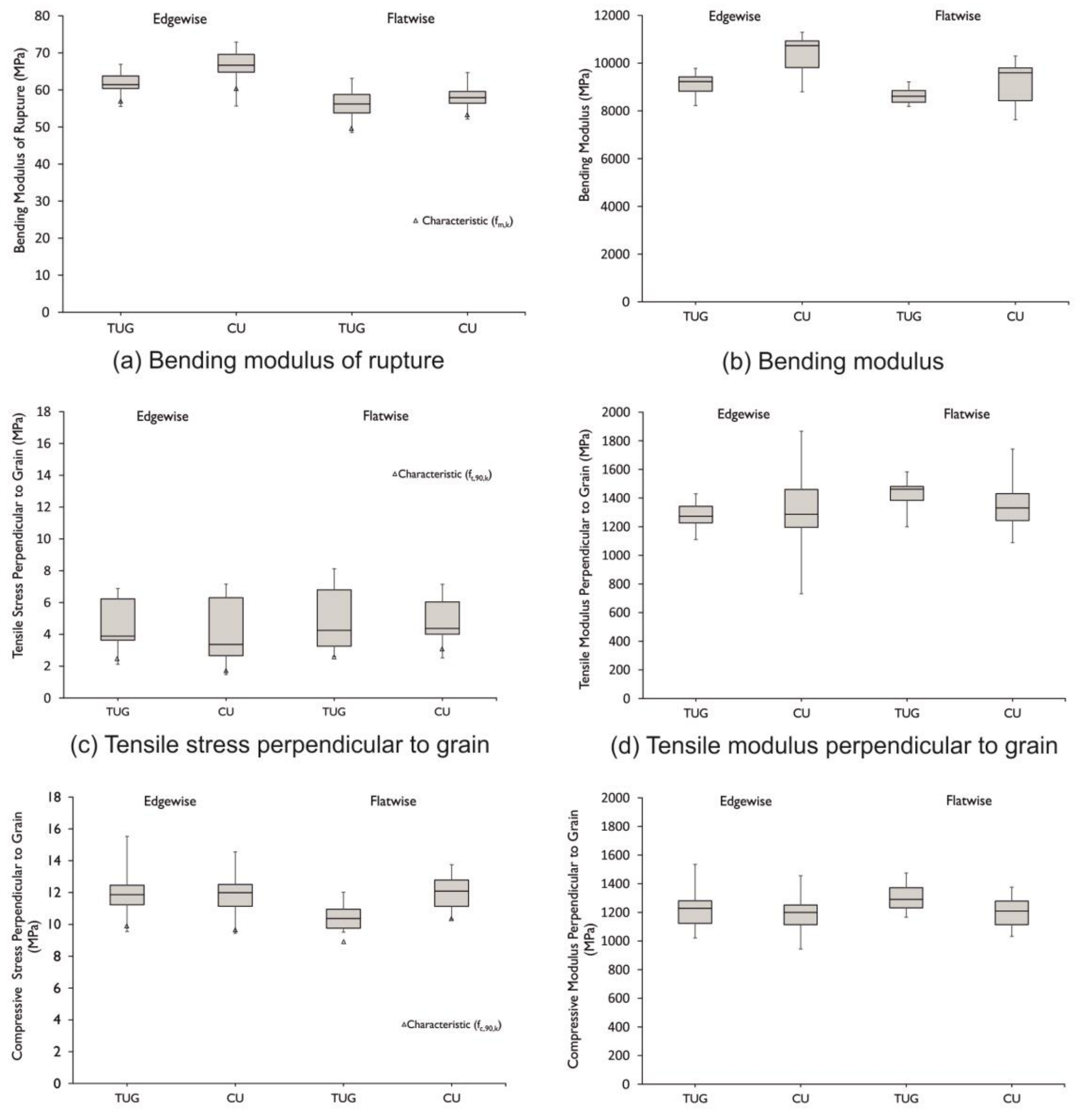
(a) Tension parallel to grain single ply board test setup

(b) Tension parallel to grain laminated section test setup

(c) Compression parallel to grain test setup

(d) Shear parallel to grain test setup

Figure 3. Experimental test methods: (a) tension single ply, (b) tension laminated section, (c) compression and (d) shear parallel to grain.



(a) Bending modulus of rupture

(b) Bending modulus

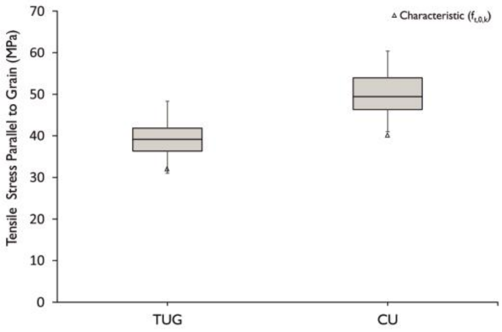
(c) Tensile stress perpendicular to grain

(d) Tensile modulus perpendicular to grain

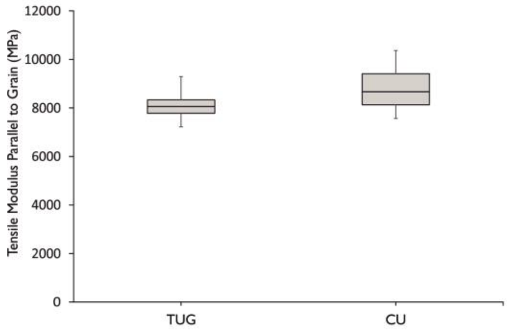
(e) Compressive stress perpendicular to grain

(f) Compressive modulus perpendicular to grain

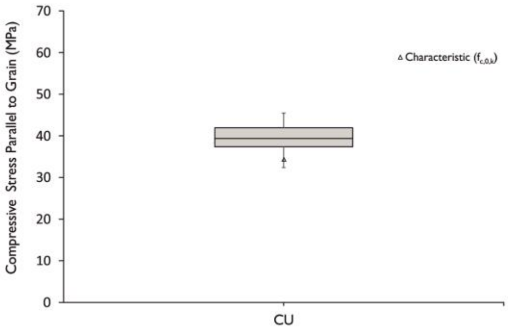
Figure 4. Experimental results and characteristic values for bending and perpendicular to grain tests.



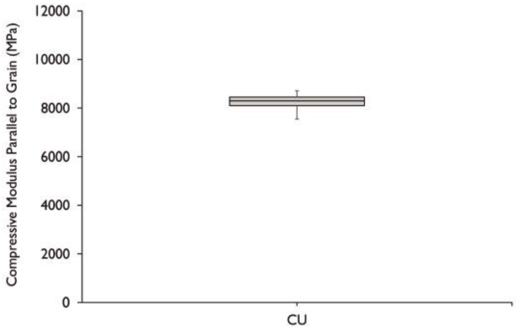
(a) Tensile stress parallel to grain



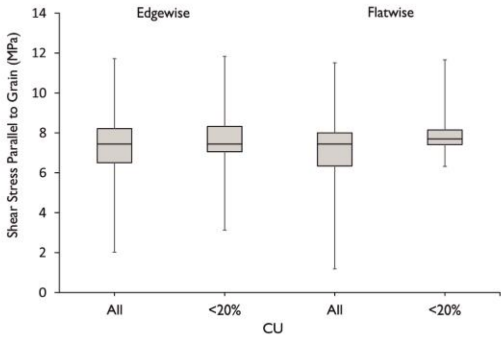
(b) Tensile modulus parallel to grain



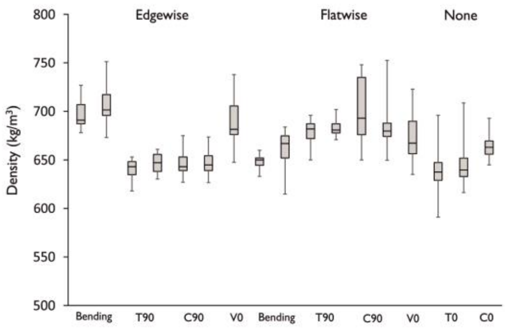
(c) Compressive stress parallel to grain



(d) Compressive modulus parallel to grain



(e) Shear stress parallel to grain



(f) Density

Figure 5. Experimental results and characteristic values for parallel to grain tests and specimen density for all tests.

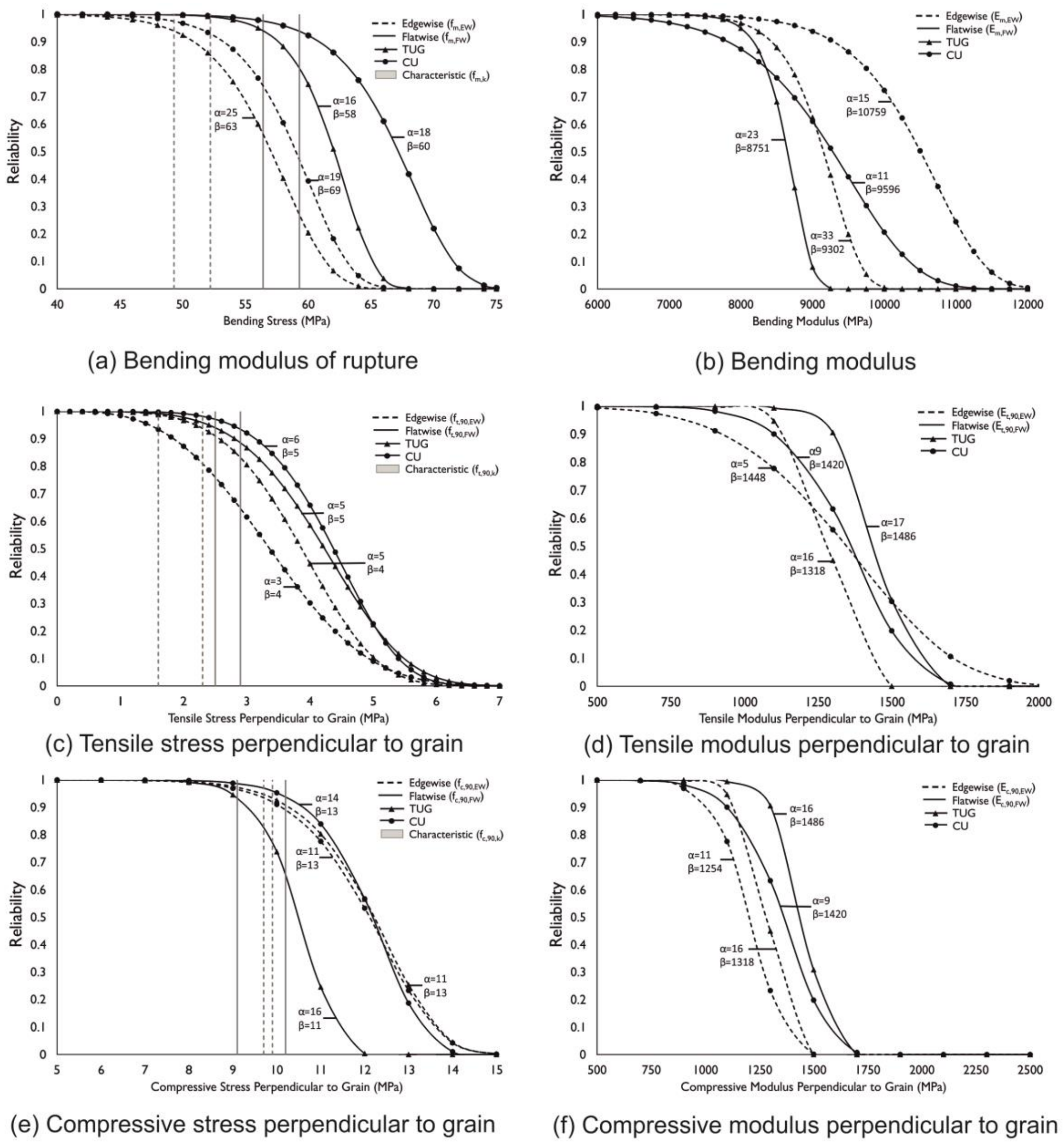
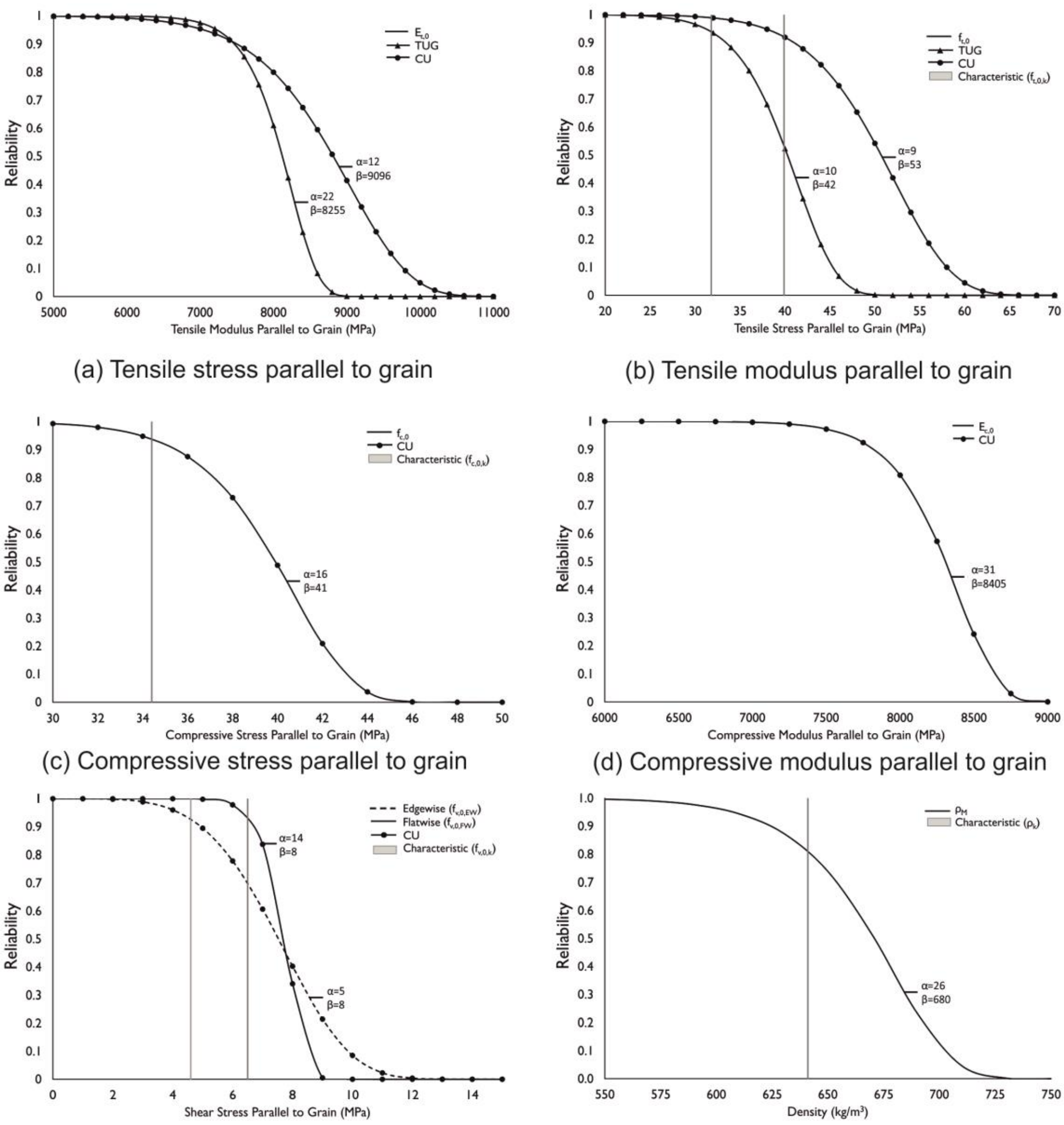


Figure 6. Reliability curves and characteristic values for bending and perpendicular to grain tests.



(a) Tensile stress parallel to grain

(b) Tensile modulus parallel to grain

(c) Compressive stress parallel to grain

(d) Compressive modulus parallel to grain

(e) Shear stress parallel to grain

(f) Density

Figure 7. Reliability curves and characteristics values for parallel to grain tests.

Table 1. Summary of specimen dimensions and sample sizes.

Test	Orientation	Dimensions (mm)	Sample Size	
			TU Graz	Cambridge
Bending	EW	2440x140x90	20	20
	FW		20	20
Compression Parallel	--	540x90x140	--	40
Compression Perpendicular	EW	70x45x90	20	20
	FW		20	20
Tension Parallel	Single-ply	2440x140x18	40	--
	Dogbone	1520x90x30	--	40
Tension Perpendicular	EW	70x45x180	20	20
	FW		20	20
Shear Parallel	EW	300x32x55	--	40
	FW		--	40

Table 2. Summary of experimental test results and characteristic values. TU Graz values are shown in white, Cambridge University values are shown in grey. The coefficient of variation (COV) is shown in parentheses.

Test Method	Strength (N/mm^2)	Orientation Edgewise (EW)	Orientation Flatwise (FW)	EW/FW
Bending	$f_{m,mean}$	61.7 (0.05)	56.6 (0.07)	1.09
		66.7 (0.06)	58.6 (0.06)	1.14
	$f_{m,k}$	56.4	49.3	1.14
		59.3	52.2	1.14
	$E_{m,mean}$	9093 (0.05)	8612 (0.03)	1.06
		10412 (0.07)	9178 (0.08)	1.13
Tension Parallel	$f_{t,0,mean}$	39.1* (0.11)		--
		50.0* (0.12)		--
	$f_{t,0,k}$	31.8*		--
		39.9*		--
	$E_{t,0,mean}$	8062* (0.05)		--
		8713* (0.10)		--
Tension Perpendicular	$f_{t,90,mean}$	3.8 (0.22)	4.2 (0.24)	0.90
		3.4 (0.32)	4.3 (0.18)	0.80
	$f_{t,90,k}$	2.3	2.5	0.92
		1.6	2.9	0.55
	$E_{t,90,mean}$	1279 (0.07)	1443 (0.07)	0.89
		1295 (0.24)	1346 (0.13)	0.96
Compression Parallel	$f_{c,0,mean}$	39.5 (0.07)		--
	$f_{c, 0,k}$	34.4		--
	$E_{c,0,mean}$	8166 (0.08)		--
Compression Perpendicular	$f_{c,90,mean}$	12.1 (0.10)	10.4 (0.07)	1.16
		12.0 (0.08)	12.1 (0.11)	0.99
	$f_{c,90,k}$	9.9	9.1	1.09
		9.7	10.2	0.95
	$E_{c,90,mean}$	1219 (0.10)	1295 (0.07)	0.94
		1197 (0.08)	1206 (0.11)	0.99
Shear Parallel	$f_{v,0,mean}$	7.4 (0.18)	7.6 (0.08)	0.97
	$f_{v,0,k}$	4.6	6.5	0.71
Density	ρ_{mean}	666 (0.05)		
	ρ_k	641		
Moisture Content	u_{mean}	8.6% (0.10)		

Notes:
*Tension parallel to grain test method differed, see Section 2.24 for more information.

Table 3. Comparison of characteristic strength and stiffness properties (mean values) as well as density (mean values) from strength classes for structural timber and glulam made of softwood and experimental testing parallel to grain in accordance with EN 408.

	Density	**Compression**		**Tension**		**Shear**	**Flexure**	
	ρ_{mean}	$f_{c,0,k}$	$E_{c,0,mean}$	$f_{t,0,k}$	$E_{t,0,mean}$	$f_{v,k}$	$f_{m,k}$	$E_{0,mean}$
	kg/m^3	MPa	MPa	MPa	MPa	MPa	MPa	GPa
Engineered Bamboo [a]	666	34.4	8166	32	8062	5	49	8612
C24 – EN 338 [b]	420	21	370	14	370	4	24	11000
GL 24h – EN 14080 [c]	420	24	300	19.5	300	3.5	24	11500
Norway Spruce [d,e]	--	44*	18254*	122*	15793*	6	48+	13361+
Glue Laminated Spruce [f]	450	32	8600	--	8472	--	50	--
Thermally Modified Beech [g]	580	48.7*	--	14	--	--	31	12800

Notes:
* Test not conducted in accordance with EN 408
+ Experimental mean
[a] Present study; [b] EN 338; [c] EN 14080; [d] Steiger et al. (2009); [e] Jenkel et al. (2015);
[f] De Lorenzis et al. (2005); [g] Widmann et al. (2012)